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THIOVEC(R) TVC NOZZLE WARM GAS ACTUATION

Conrad R. Huskey

Thiokol Corporation

Prepared for:

Naval Surface Weapons Center

30 June 1975

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THIOL CORPORATION
ELKTON DIVISION
ELKTON, MARYLAND

FINAL PROGRAM SUMMARY REPORT

THIOVEC[®] TVC NOZZLE WARM GAS ACTUATION
CONTRACT N60921-74-C-0318

PREPARED FOR:

NAVAL SURFACE WEAPONS CENTER
WHITE OAK LABORATORY
SILVER SPRING, MARYLAND 20910

PREPARED BY:

MR. CONRAD HUSKEY
SENIOR PROJECT ENGINEER

JUNE 30, 1975

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13. ABSTRACT <p>Warm gas actuation of a THIOVEC® TVC nozzle was demonstrated using a solid propellant gas generator and a solenoid operated bi-stable flapper-type warm gas valve. The TVC nozzle's dynamic characteristics were obtained in a series of bench tests with simulated motor chamber pressure producing the resistive torques normally experienced under motor operating conditions. These bench tests provided frequency response, phase lag, slew rate, and system hysteresis data which proved the system to be a viable candidate for low-maintenance, cost-effective TVC nozzle system applications.</p>			

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In Reply Refer To:
E125-75

June 30, 1975

Naval Surface Weapons Center
White Oak Laboratory
Silver Spring, Maryland 20910

Attention: Mr. Eugene Eizufon, WR-12

Subject: Final Program Summary Report;
THIOVEC[®] TVC Nozzle Warm Gas Actuation

Reference: Contract N60921-74-C-0318

Gentlemen:

We are pleased to submit this final program summary report marking the conclusion of a successful Warm Gas Actuation demonstration program of the THIOVEC[®] TVC nozzle.

The enclosed report contains summaries of the nozzle calibration and Warm Gas Actuation tests which have verified the elimination of hydraulics from a thrust vector control nozzle as practical.

If you have any questions concerning this report, please contact either Joseph Reardon, Program Manager, or F. I. Ochs, Manager, Contracts Administration.

Very truly yours,

THIOKOL CORPORATION
ELKTON DIVISION



T. M. Davis
General Manager

JER/cm

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ELKTON, MARYLAND

FINAL PROGRAM SUMMARY REPORT

MOVEC[®] TVC NOZZLE WARM GAS ACTUATION
CONTRACT N60921-74-C-0318

PREPARED FOR:

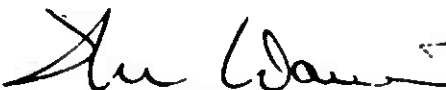
NAVAL SURFACE WEAPONS CENTER
WHITE OAK LABORATORY
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JUNE 30, 1975

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General Manager

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FOREWORD

This Final Report of the THIOVEC® TVC Nozzle Warm Gas Actuation program is submitted to the Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, Maryland, in accordance with the requirements of Contract N60921-74-C-0318.

The following Thiokol personnel contributed to this program:

Conrad Huskey	Senior Project Engineer
Richard Bourdon	Design Engineer
Carl Gonce	Test Engineer
Joseph Reardon	Program Manager

Mr. Conrad Huskey was responsible for the technical direction of the program and was the author of this Final Report. Mr. Eugene Elzufon of the Naval Surface Weapons Center was responsible for the technical coordination and monitoring of this Navy-sponsored program.

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1.0 INTRODUCTION

A two-phase program was conducted to demonstrate warm gas actuation of the THIOVEC[®] TVC nozzle system. The culmination of the effort was warm gas actuation bench tests which demonstrated feasibility in Phase I and characterized nozzle performance in Phase II. During the tests, the THIOVEC[®] TVC nozzle was subjected to simulated chamber pressure, duty cycle, and operating time similar to that which may be experienced aboard a typical underwater missile. The nozzle used was refurbished from the THIOVEC[®] underwater static test performed under Navy Contract Number N00123-73-C-2925.

Phase I was initiated with the design of the warm gas actuation system, procurement of the warm gas servocontrol valve, and manufacture of the warm gas generator. Upon completion of the system design, the remaining components, such as tubing orifices and fixtures, were fabricated. After assembly of the system, nitrogen gas was used for system check-out prior to the warm gas feasibility demonstration test. Phase I was concluded with the successful warm gas actuation test wherein all test objectives were met and performance exceeded that required. The average nozzle slew rate was 210 deg/sec from null to 90% of full deflection in response to a step command to full nozzle deflection. The nozzle's 90° phase lag and -3 db response point, determined using cold gas, occurred at 20 to 25 Hz.

Characterization of the warm gas actuation system, accomplished in Phase II, provided maximum and average slew rates, phase lag, response, and nozzle hysteresis data. The maximum slew rate was 300 deg/sec and the average was 165 deg/sec. The 90° phase lag occurred at 20 Hz and the -3 db response was at 25 Hz. The hysteresis in the system was measured at ± 0.2 deg over full range of deflection.

2.0 PROGRAM OBJECTIVES

Both the Navy and Thiokol are interested in achieving a low cost, minimum maintenance TVC nozzle system for use in underwater missiles. Studies have shown that the THIOVEC[®] TVC nozzle is low in cost relative to the other TVC nozzles, and underwater bench tests and an underwater static test have demonstrated the feasibility of that TVC system for use in underwater missiles.

The program objective is to further demonstrate features which permit the realization of low cost TVC systems. Specifically, the feasibility of warm gas actuation of the THIOVEC[®] nozzle was to be demonstrated. The warm gas actuation system minimizes maintenance since prelaunch check-out is not required because the possibility of hydraulic fluid leaks is absent. Of importance in system cost effectiveness studies is the fact that such a warm gas actuation system permits launching from sites which are inaccessible for the purpose of performing the mechanical prelaunch check-out ordinarily required when hydraulic actuation is used.

3.0 DISCUSSION

3.1 General

Work in Phase I was directed toward the verification of test hardware, which was a necessary first step before characterization of the pneumatic actuation system in Phase II. Electrical and mechanical hardware was involved in building the pneumatically actuated TVC nozzle system. Mechanical hardware included: 1) an existing THIOVEC[®] TVC nozzle; 2) a bi-stable warm gas servocontrol valve which is a modification of an existing production valve; and 3) a standard test weight warm gas generator. The electrical equipment included an electronic servovalve controller, the command signal electronics, and the standard test data acquisition equipment to measure and record the pressures, temperatures, and nozzle dynamic characteristics of interest. Phase I, therefore, included all work necessary to design, fabricate, and test the TVC system through the first warm gas actuation system demonstration test. Work in Phase II was directed toward characterizing the dynamic response of the THIOVEC[®] TVC nozzle using a warm gas actuation system. A total of six warm gas tests were conducted in this program: one in Phase I and five in Phase II. The first two tests in Phase II were required to clear an instrumentation problem prior to initiating characterization tests. A brief description of the THIOVEC[®] nozzle is presented in Appendix A.

3.2 Warm Gas Actuation System

A schematic showing the test arrangement, designed for single plane motion, is presented in Figure 1. Omniaxial motion can be achieved using an additional control valve, two additional restrictors, and tubing to operate the vector seals in the other plane of motion 90° to those shown. The warm gas generator is a standard test vehicle in use at the Elkton Division of Thiokol and is designated TC-1. The propellant grain is an end-burning type 3.75 inches in diameter and 2 inches long. Since this standard grain is larger than that required for supplying the actuation gas, a secondary flow orifice was installed in the gas generator to bleed off the excess gas supply. The Thiokol-developed propellant, TP-Q-3100, is a low flame temperature (1740°F) propellant whose combustion products are free of significant particulate matter and toxic or corrosive chemical species. The Flow Restrictors permit pressurization of one vector seal actuator while sufficiently restricting flow from the generator into the venting side so as to produce the pressure differential necessary to vector the nozzle. The warm gas servocontrol valve is a bi-stable flapper type proportionally controlled with a pulse modulated command signal. The THIOVEC[®] nozzle is the same as that used in the previously mentioned underwater static test. To permit an economical test program, brackets were attached to this omniaxial nozzle so that it vectors in one plane only. This reduced the required number of pneumatic control valves from two to one per test and also reduced test setup time.

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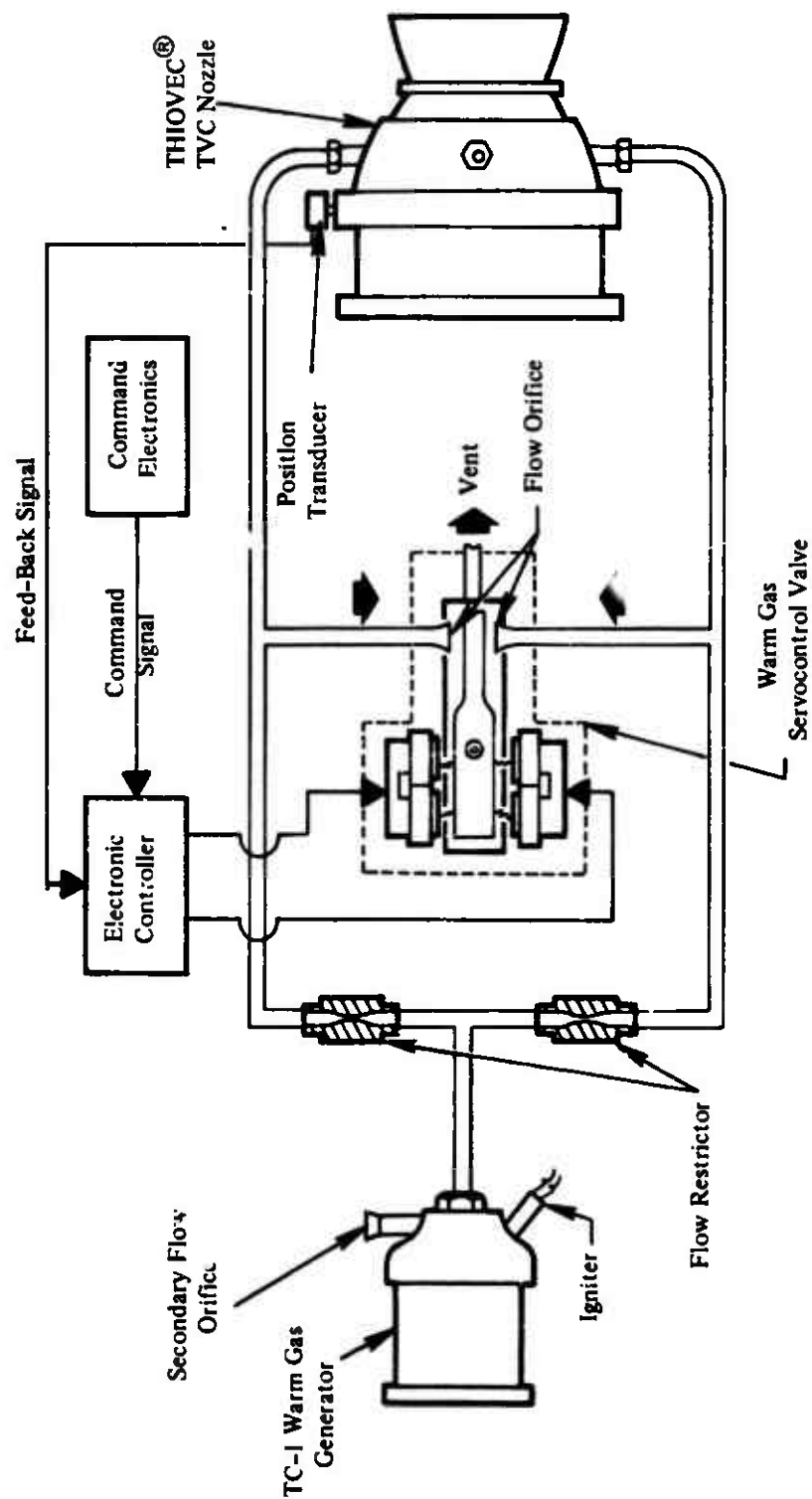


FIGURE 1. PNEUMATIC CONTROL—THIOVEC® TVC NOZZLE
TEST ARRANGEMENT FOR SINGLE AXIS MOTION

Cold gas tests were conducted prior to each warm gas test to assure proper functioning of the TVC nozzle and control electronics. The cold gas, N_2 , was introduced into the system through the gas generator chamber, without the solid propellant grain installed. For warm gas testing, the N_2 line was disconnected from the gas generator chamber and the propellant grain and igniter installed; the TVC system was then ready for the warm gas test.

Design calculations for the warm gas actuation system were conducted using the following assumptions:

- 1) Sizing of the system would permit a maximum gas generator pressure of 2000 psia under conditions of flow through the secondary orifice and one restrictor; the other restrictor was assumed closed by the valve flapper's being held in the hard-over position long enough for the gas generator to respond to the change in nozzle flow area.
- 2) Maximum pressure differential across opposing vector seals was assumed to be 1000 psid.
- 3) The actuation system was sized to provide a maximum nozzle slew rate of 200 deg/sec at an assumed gas stagnation temperature in the vector seals of 660°R.
- 4) It was assumed that, at the time maximum flow rate through the restrictors occurred, the down stream pressure was low enough to permit sonic flow through the restrictors.

Maximum change in vector seal volume of 0.343 in.³ occurs when the nozzle travels from the fully deflected position of 10 degrees vector angle to the null position. To achieve the maximum slew rate of 200 deg/sec, the volumetric rate of flow into the vector seal causing that deflection must be 6.86 in.³/sec. Using the thermochemical properties of the gas generator propellant and the maximum chamber pressure, the maximum weight flow rate was calculated to be 0.026 lbs/sec. Based on this maximum flow rate, the gas generator propellant grain, secondary flow orifice, and restrictor orifices were then sized.

3.3 Description of Tests

The following is an outline summarizing the cold and warm gas testing of the THIOVEC[®] TVC nozzle:

1) Sizing the Warm Gas System for TC-1 Generators

- a) Verify size of restrictors and secondary orifices for a 1500 psia nominal generator operating pressure and measure temperature of exhaust gas and tubing during generator operation to assure absence of excessive heating.
- b) Equipment: TC-1 gas generator; stainless steel tubing and fittings; restrictors; and secondary orifice.

2) Cold Flow Tests

a) Cold Gas Control System Checkout.

- i) Cold gas pressure 500 psig.
- ii) Equipment: (a) servocontroller; (b) PDM valve; (c) TC-1 gas generator without propellant or igniter; (d) restrictors and tubing to valve and nozzle.

b) Nozzle and Control System Tests.

- i) Cold gas actuation system supply pressure 1500 psig.
- ii) Equipment: (a) servocontroller; (b) PDM valve; (c) TC-1 gas generator without propellant or igniter; (d) tubing, restrictors, and tubing to valve and nozzle.
- iii) Nozzle internal pressure at 1500 psia to simulate motor chamber pressure.
- iv) Nozzle test: system gain adjusted to maximize response and to eliminate nozzle overshoot prior to data acquisition of following tests:
 - Duty cycle (see Figure 2).
 - Hysteresis loop.
 - Nozzle response (-3 db point) and phase lag (90° shift point).

3) Warm Gas Tests

- a) Operating pressure of TC-1 gas generator was 1500 psia nominal.
- b) Nozzle internal pressure 1500 psia simulating motor chamber pressure.
- c) Equipment: same as cold gas except that a propellant grain, igniter, and primary orifice are used and the cold gas system is disconnected.
- d) Tests:
 - i) Duty cycle (see Figure 2).
 - ii) Hysteresis loop.
 - iii) Nozzle response (-3 db point) and phase lag (90° shift point).

The gas generator used to provide the driving force to the THIOVEC[®] nozzle is a standard end-burning generator designated TC-1. The propellant used was TP-Q-3100. The gas generator, which has a flow rate in excess of that required, used a secondary flow control orifice to permit bleed-off of excess gas. A test arrangement as shown in Figure 3 was made to verify the orifice sizes. The gas generator was assembled in the same manner as that used for the nozzle actuation tests with the exception that the valve was deleted and the gas permitted to dump overboard after passing through the two restrictors. The intended operating pressure of the gas generator was to be 1500 psia, with both restrictors and the secondary orifice venting to atmosphere.

The tubing and fittings used to duct the gas from the generator were of 316-type stainless steel and were standard commercial items. The secondary and restrictor orifices were made from stainless steel pipe plugs which were drilled to the proper orifice diameters. The drilled plugs could then be easily assembled as they simply threaded in place. All tubing was reused several times without damage or rework except for cleaning.

Thermocouples were placed on the outside of the tubing and in the exhaust stream. The temperature of the tubing at TC-1 and -3 locations was approximately 1500°F. The approximate static exhaust gas temperature measured at the discharge, locations TC-1 and -4, was approximately 1100°F.

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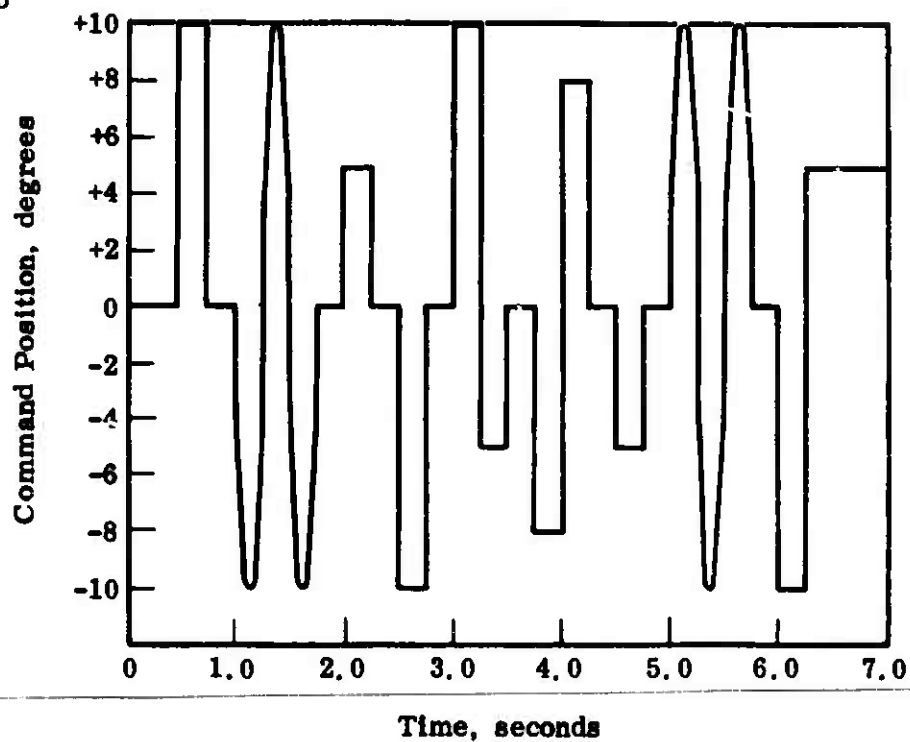


FIGURE 2. NOZZLE COMMAND DUTY CYCLE

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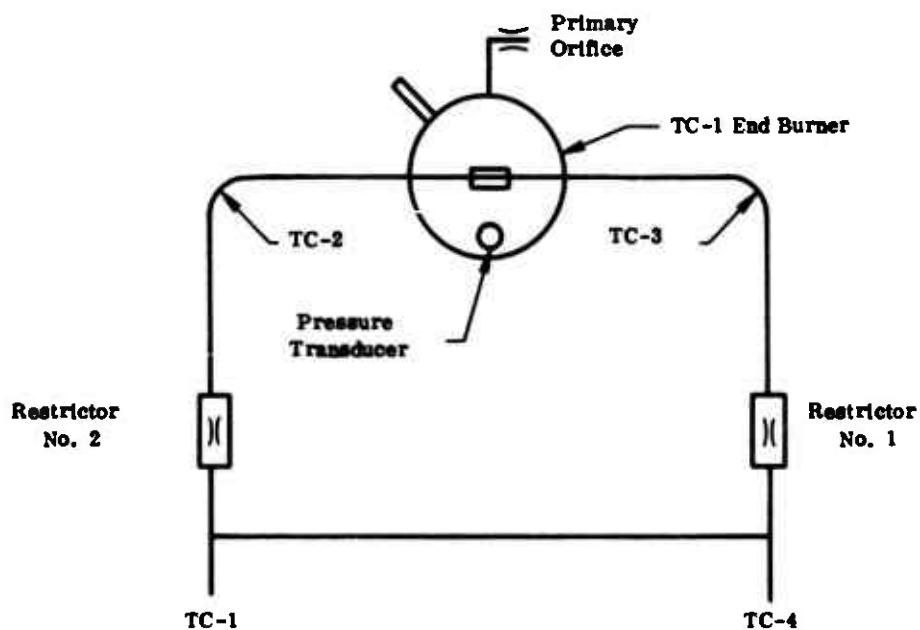


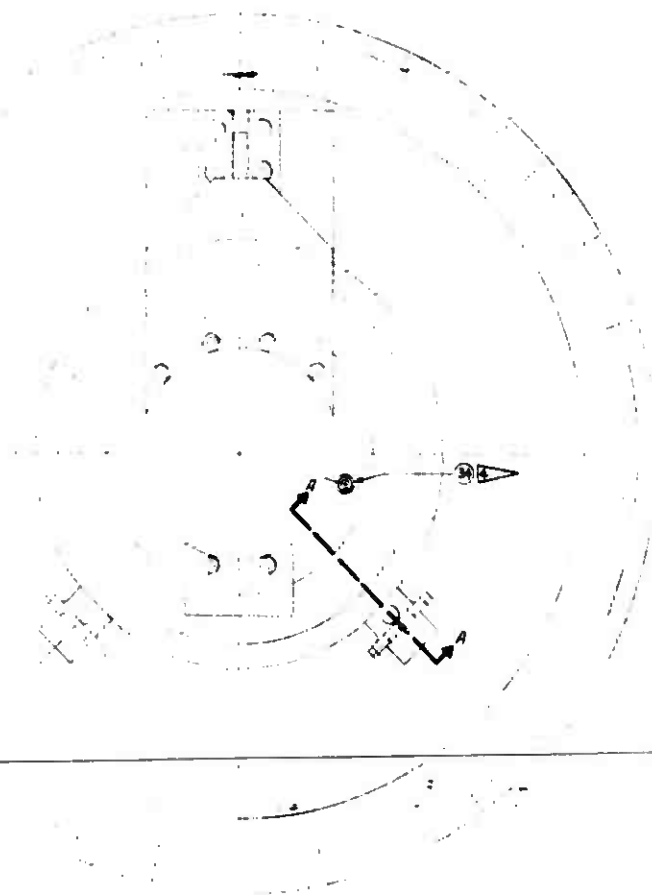
FIGURE 3. TEST ARRANGEMENT

The THIOVEC[®] nozzle assembly, shown in Figure 4 (E28478), was assembled with only two vector seals for single plane nozzle motion instead of the number required for omniaxial nozzle motion to simplify the test arrangement and to control electronics. A guide bar and rubbing blocks were used on the nozzle to act as a guide to limit actuation to only one plane. This successfully minimizes the cost and complexity of the nozzle tests. It should be noted that the same vector seal assemblies were used for all the test sequences, including the cold gas actuation tests, to demonstrate their compatibility with the warm gas actuation system. A photograph of the nozzle assembly is shown in Figure 5.

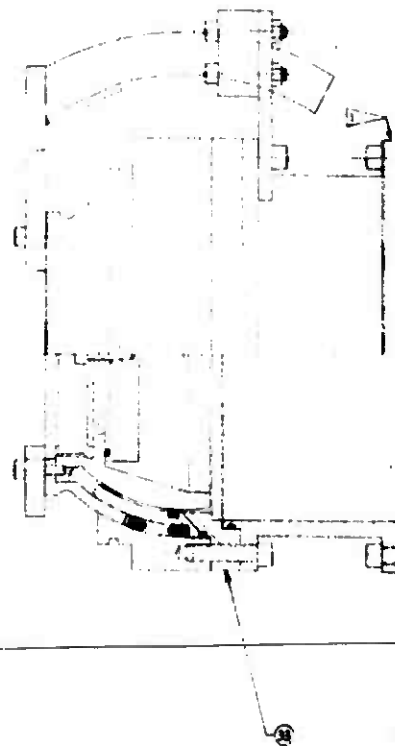
After assembly the nozzle was checked for adequate clearance by performing an internal nozzle pressure versus nozzle axial deflection test to verify that the grease bearing was assembled properly. After successfully completing the test, the nozzle was placed in a static test bay where all nozzle testing was conducted. The nozzle was attached to the TC-1 gas generator in accordance with drawing E27647, presented in Figure 6. A photograph of this assembly is shown in Figure 7. The primary orifice and igniter were removed, the flex lines and valves from the cold gas source (GN₂ bottles) were attached, and the cold gas actuation testing of the nozzle completed. The pressure from the GN₂ bottles was regulated to achieve 1500 psia inside the TC-1 pressure chamber. The test setup was identical for both Phase I and Phase II program.

The arrangements for the cold gas tests were the same as those for the warm gas tests except that the primary orifice, igniter, and propellant grain were not used. The gas exited through a vertical pipe and was directed by means of a tee to two 1/4 inch O.D. stainless steel tubes. Two 0.049 inch diameter restrictors were installed in the line between the gas generator and the valve. The gas flow through each restrictor was directed to the vector seals by means of the warm gas servocontrol valve. The control valve is a bi-stable, flapper-type valve which operates in a pulse duration modulation (PDM) mode and provides proportional control to the nozzle position. It is similar to the single stage flapper valves developed at Aeromutronic Division, Philco-Ford Corporation for the Shillelagh Jet Reaction Control system, and now used for the pilot system of the two-stage Minuteman Roll Control valve which is currently in production.

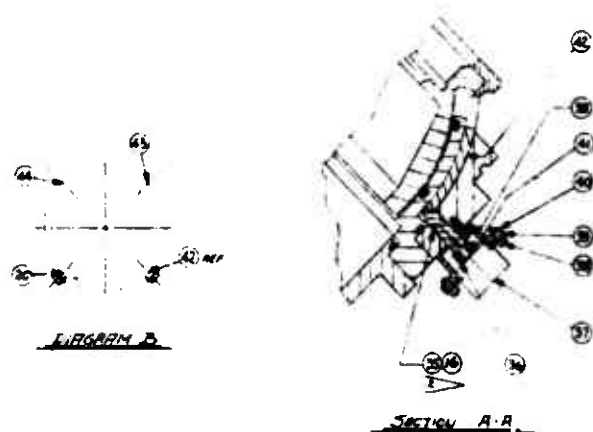
The valve has a flexurally-mounted armature (flapper) within a cylindrical body which incorporates magnetic pole pieces and flow orifices. The only moving part of the control valve is the flexure-mounted flapper. The flapper is made of ferromagnetic alloy, welded to a stainless steel flexure. The flexure suspends the flapper between two sets of magnetic pole pieces: gas enters the valve through either of the two control valve flow orifices, as selected by energizing the appropriate solenoid coil and by moving the flapper to close one of the orifices. Gas entering the valve then exhausts through the vent port.



EXTEND ← RETRACT



-02 CONFIG (SHOWN)
(OTHERWISE SAME AS -01 CONFIG)
-04 CONFIG



SEE DIAGRAM B

NOTES:

- 1 IDENTIFY PER P-2001-2.
- 2 APPLY GREASE (ITEM NO. 16) TO MATING SURFACES PRIOR TO ASS.
- 3 TORQUE SCREWS (ITEM NO. 30).
- 4 TORQUE SCREWS (ITEM NO. 27).
- 5 TORQUE SCREWS (ITEM NO. 2).
- 6 TORQUE SCREWS (ITEM NO. 2).
- 7 APPLY THREAD COMPOUND (1) HEADS OF SCREWS.
- 8 LUBRICANT (ITEM NO. 16) TO ITEM NO. 15 OR 16 SO THAT GA (OUTER RACES ARE FILLED).
- 9 COAT ENTIRE SURFACES OF (ITEM NO. 17), BACK-UP RINGS (1) SEALS (ITEM NO. 19) WITH LUBR. TO INSTALLATION.
- 10 -03 CONFIG SAME AS -01 REQD AND LESS ITEMS 1, 2, 3, 4.
- 11 -04 CONFIG SAME AS -02 REQD AND LESS ITEMS 1, 2, 3, 4.
- 12 ADJUST RUBBER BLOCKS (1) TO .002 TO .004 TOTAL CLEARANCE AND REM OF GUIDE BAR (1).

FIGURE 4. NOZZLE ASSEMBLY

-10-

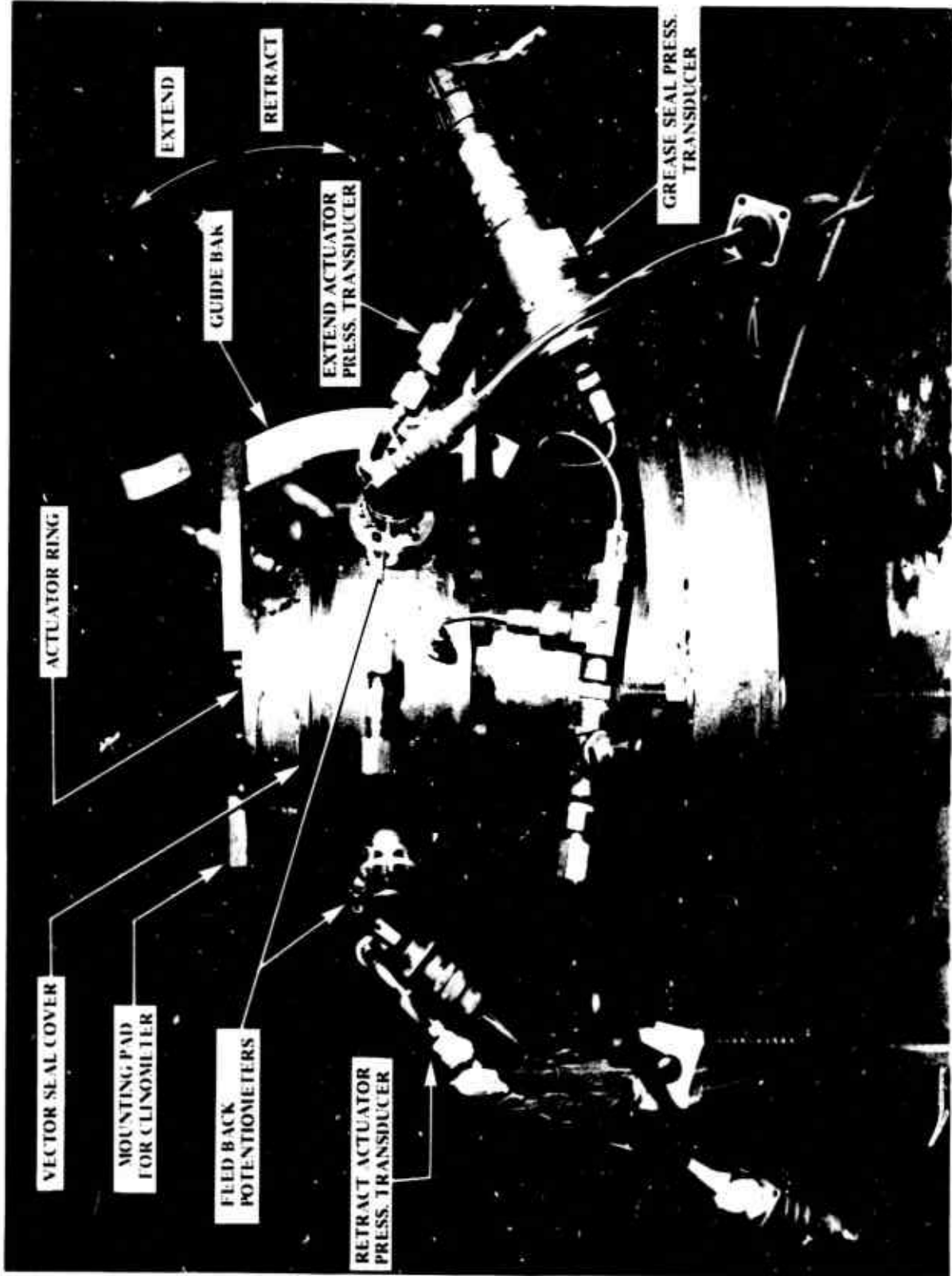
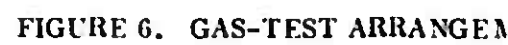
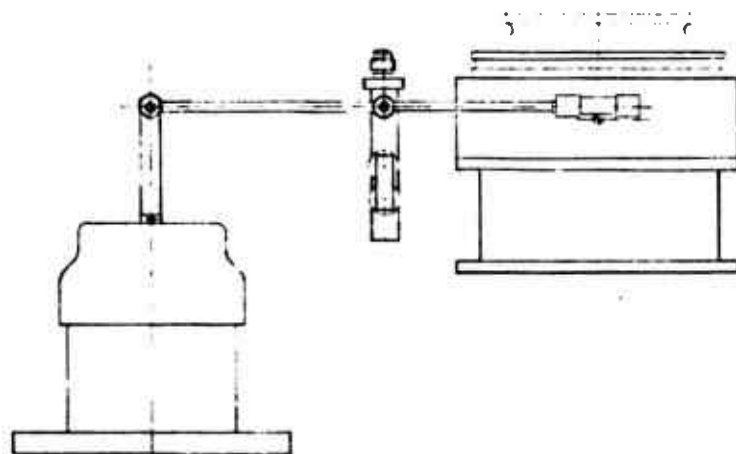
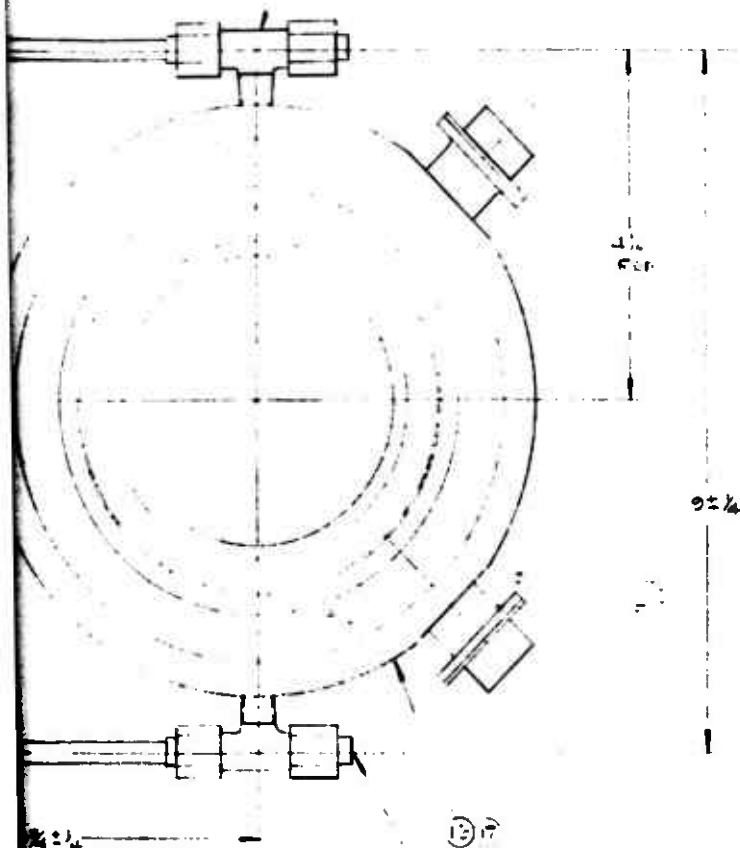


FIGURE 5. NOZZLE ASSEMBLY, TEST ARRANGEMENT





TEST ARRANGEMENT

TO PRESSURE
TRANSFORMER

1	1	10	E27647-01	NOZZLE ASSY		
1	1	11	E27647-02	NOZZLE ASSY		
1	1	12	2000	CONTROL VALVE		
1	1	13		GAS GENERATOR		

E27647

2	2	14	30750	WATER	5/8" NPT PLUG	
2	2	15	30750	WATER	TEE	
2	2	16	30750	WATER	TEE	
2	2	17	30750	WATER	REDUCER	
2	2	18	30750	WATER	CONNECTOR	
2	2	19	30750	WATER	CONNECTOR	
2	2	20	30750	WATER	5/8" NPT PLUG	
2	2	21	30750	WATER	ELBOW	
2	2	22	30750	WATER	SLEEVE	
2	2	23	30750	WATER	NUT	
2	2	24	30750	WATER	TEE	
2	2	25	30750	WATER	NIPPLE	

ITEM NO	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION
---------	------------	------------------------	-----------------------------	----------	---------------

LIST OF MATERIAL OR PARTS LIST

DESIGN APPROVAL DRAWN BY CHECKED BY ENGINEER DATE PROJECT NO. SHEET NO.		THIOVEC GAS TEST ARRANGEMENT	
DESIGN APPROVAL DRAWN BY CHECKED BY ENGINEER DATE PROJECT NO. SHEET NO.		CODE IDENT NO. DATE 07200 J E27647	

ARRANGEMENT. DRAWING E27647

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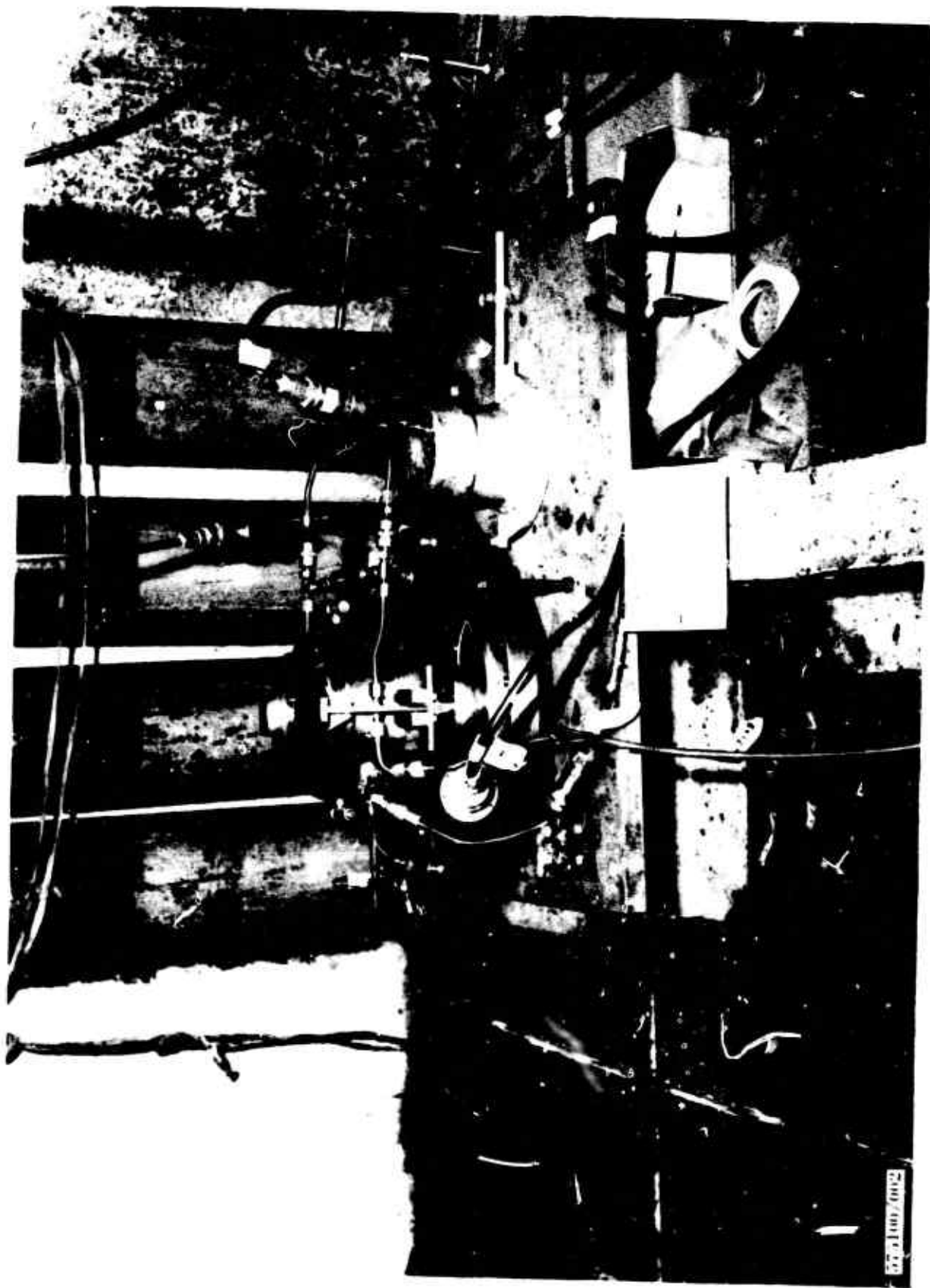


FIGURE 7. NOZZLE TEST ARRANGEMENT

One valve is required for each control axis. The valve operates in a PDM mode to control the pressure differential between the opposing THIOVEC[®] nozzle vector seals as shown in Figure 1. Gas flow to the vector seals is introduced through a restrictor in the inlet line and is vented through the control valve. The relative sizes of the valve flow orifices and restrictors are such that with the flapper held in a hard-over position, the control valve will vent all the gas entering the inlet restrictor as well as venting the actuator on that side. All of the gas coming through the other restrictor is retained so that differential pressure is obtained.

With the control valve operating in a pulse duration modulation (PDM), the flapper dwell time on each of the restrictors controls the amount of gas in the vector seals. This establishes the differential pressure between opposing vector seals, and the resulting net torque is applied to the nozzle as a function of command.

During the warm gas tests, the flapper cycled from one flow orifice to the other at a constant cyclic rate of 60 Hz. The dwell time on either restrictor was controlled from zero to 100% of the cycle period. The PDM command is expressed on a scale from -100% to +100%, where -100% represents continuous dwell on one restrictor, +100% represents continuous dwell on the other restrictor, and 0 represents a condition where the flapper dwells 50% of the time on one restrictor and 50% on the other. These commands would correspond respectively to nozzle position of hardover one way, hardover the opposite direction, and null. Intermediate positions for proportional control are attained with PDM commands proportional to the position desired.

The PDM signal to the valve is generated in an integrated servoamplifier. A summing amplifier is used to compare the command and feedback signals in the pitch and/or yaw axes. The command signals are input to the amplifier module as analog voltages. The feedback signal is generated by the position indicating potentiometers attached to the nozzle.

The command and feedback signals are compared in one amplifier and summed with the PDM waveform. For improved frequency response a rate compensation network was included in the summing amplifier. The valve driver energizes one valve coil when the summing amplifier output is positive and the opposite coil when the output is negative, thus generating the percent PDM command at the waveform generator frequency. Only the summing amplifier and driver circuit need be duplicated for the second control axis.

The propellant grain used for the warm gas tests was an end-burning type which burned for a nominal action time of 6 seconds at 90% of maximum pressure. The propellant's low flame temperature and combustion products, which were free of significant solid particulate and toxic or corrosive elements, proved highly compatible with the nozzle and actuation system hardware.

E125-75

Cold gas tests were conducted before the warm gas tests to assure that the TVC nozzle and control system functioned properly prior to testing with warm gas.

Test data acquisition included internal nozzle pressure simulating motor chamber pressure, nozzle actuation supply pressure, vector seal (actuator) pressure, nozzle position, nozzle command, and nozzle bearing lubrication pressure. The data was acquired both digitally and as analog.

4.0 TEST RESULTS

4.1 General

Three types of tests were conducted using warm gas:

- 1) Typical duty cycle to determine general response characteristics and response to step function command (Figure 2).
- 2) Command input versus nozzle position at a finite frequency to determine hysteresis loop.
- 3) Frequency response and phase lag.

For the three final warm gas tests the nozzle was not dismantled or cleaned; all tests were completed the same day. The nozzle was checked with cold gas prior to proceeding to the next warm gas test to verify proper operation. The first two tests were conducted with a maximum generator chamber pressure of 1680 psia. The last test had the primary orifice increased to provide a slightly lower (200 psia) pressure and a longer action time to ensure sufficient action time to accomplish the frequency sweep.

4.2 Duty Cycle Tests

The average slew rate from time of command signal to 90% of full command deflection 10 degrees was nominally 165 deg/sec with a maximum slew rate of 297 deg/sec. In all responses to step command there was an 0.018 to 0.020 second interval from the time of command signal to the first motion of the nozzle. No nozzle overshoot occurred in any of the nozzle's responses to the duty cycle indicating that the nozzle had been critically damped. Figure 8 presents the test results showing the commanded duty cycle and the nozzle response. Figures 9 and 10 present the pressure-time curves of the gas generator (supply) pressure and the vector seal actuation pressures.

The maximum pressure differential across the vector seals occurred as the nozzle was reaching the commanded position. At the pressure spike the differential pressure was 685 psig. The spike quickly dropped off to a steady differential pressure of 420 psig. Actuation torque, developed during the pressure spike, was 1063 in.-lbs and at the more steady differential pressure condition the torque developed was 650 in.-lbs.

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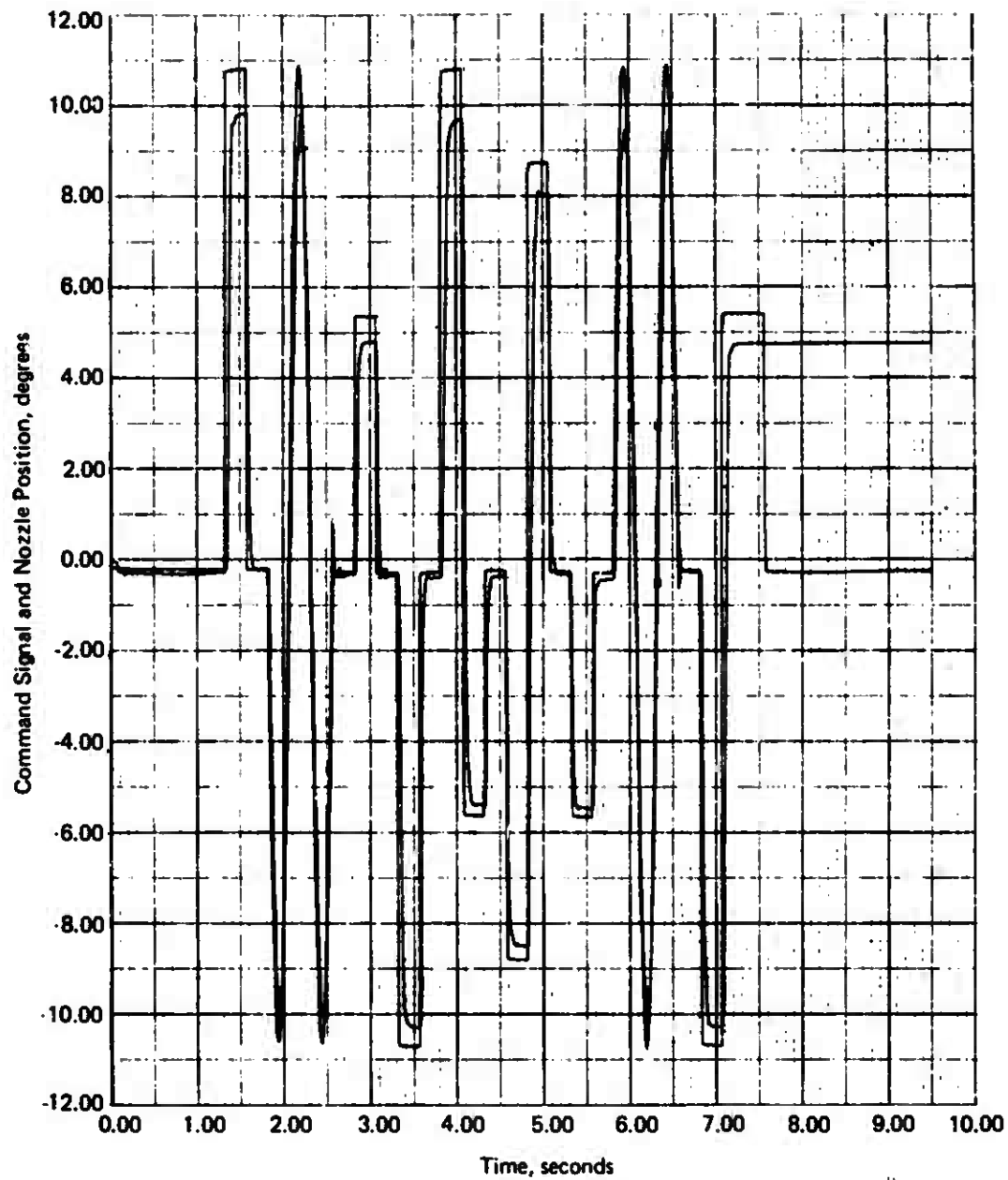


FIGURE 8. DUTY CYCLE TEST RESULTS

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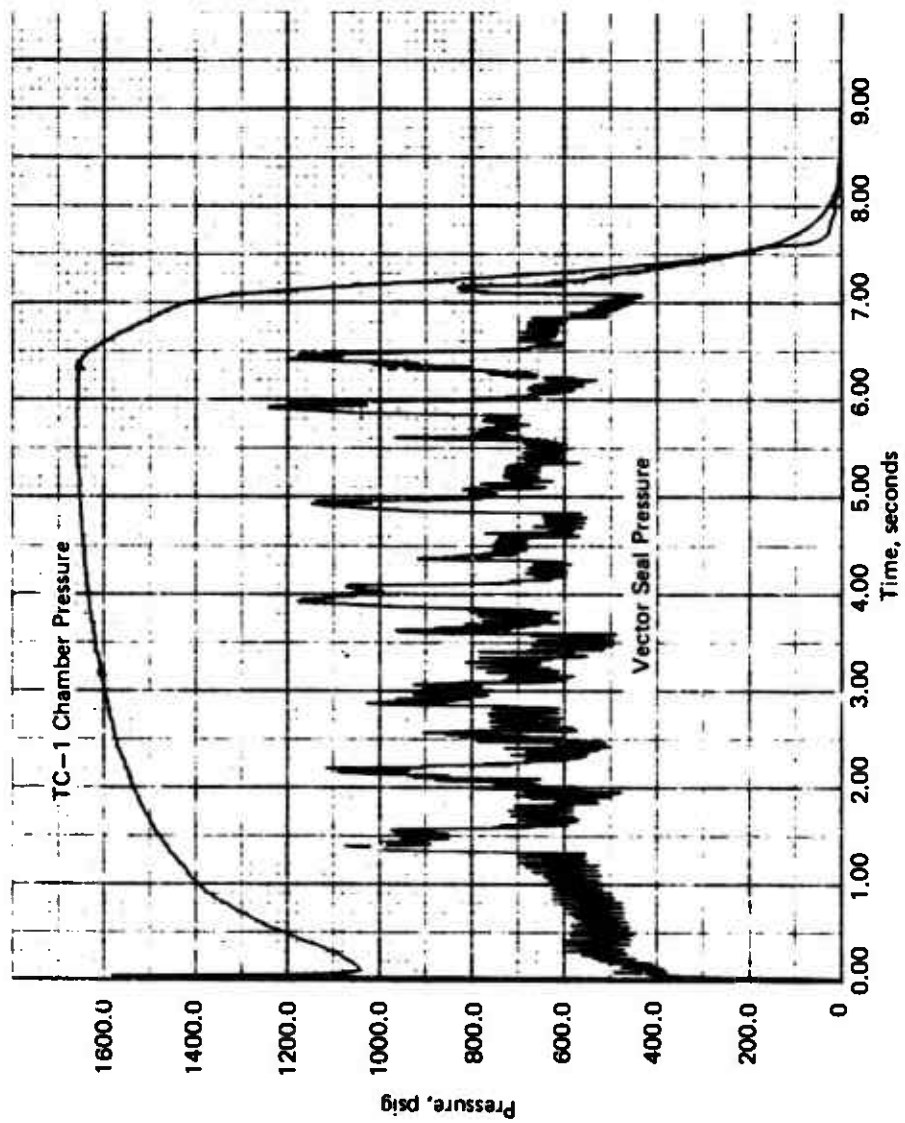


FIGURE 9. DUTY CYCLE, CHAMBER AND VECTOR SEAL PRESSURE

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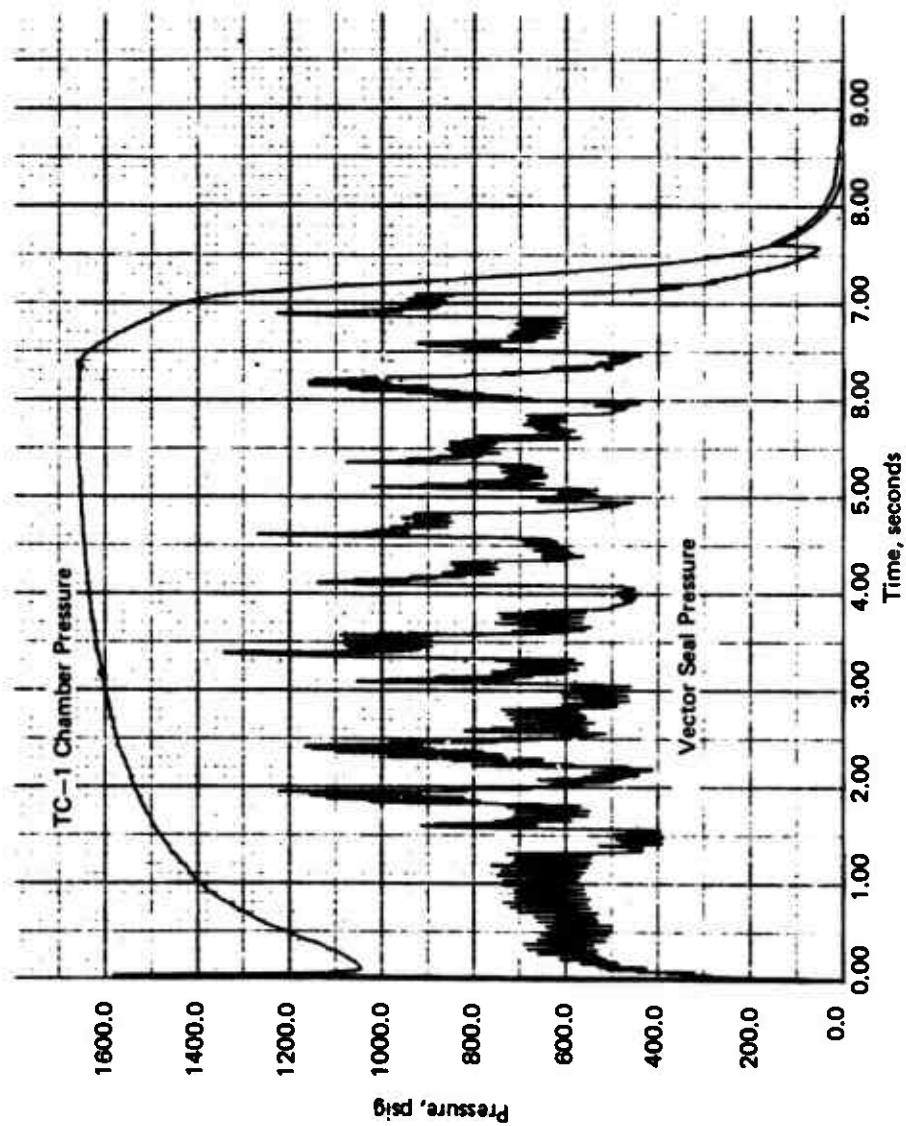


FIGURE 10. DUTY CYCLE TEST, CHAMBER AND VECTOR SEAL PRESSURE

4.3 Command Input Versus Nozzle Position (Hysteresis Loop)

The nozzle hysteresis was determined using a triangular wave command input of 0.3 Hz and a full nozzle deflection command of $\pm 10^\circ$. The hysteresis loop of the nozzle is shown in Figure 11. Figures 12 and 13 present the pressure-time curves of the gas generator (supply) pressure and the vector seal actuation pressures.

4.4 Frequency Response and Phase Lags

The frequency response and phase lags were measured while imposing a sinusoidal frequency sweep of $\pm 2.5^\circ$ amplitude. The -3 db point occurred at 25 Hz with the 90° phase lag occurring at approximately 20 Hz. Figure 14 presents the test results showing the commanded frequency sweep and nozzle response. Figures 15 and 16 present the pressure-time curves of the gas generator (supply) pressure and the vector seal actuation pressures. Figure 17 presents a plot of nozzle frequency response, expressed in decibels, versus the sinusoidal frequency. The nozzle response in decibels is computed using the following expression:

$$\text{decibels} = 20 \log_{10} AR$$

where AR, the amplitude ratio, is the ratio of nozzle position to nozzle command.

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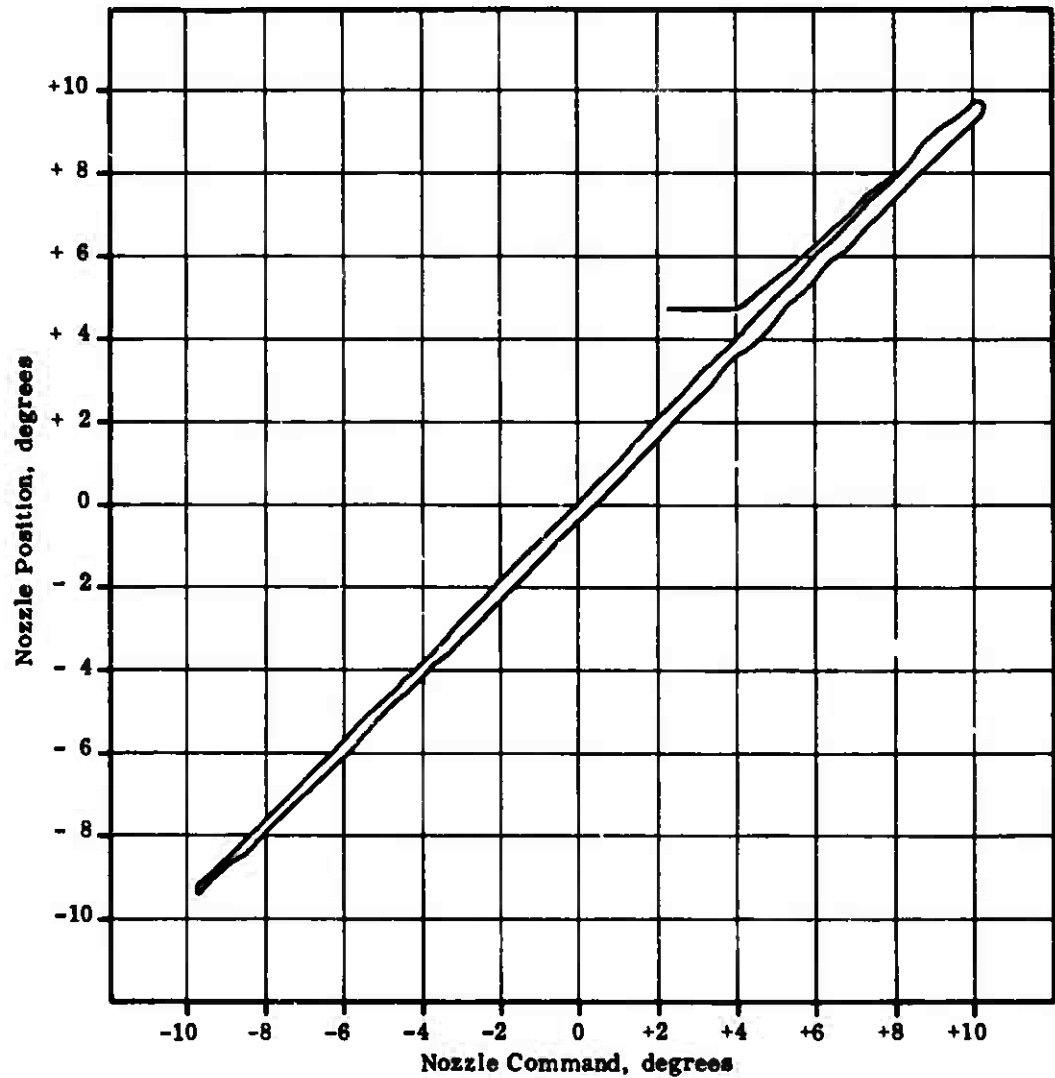


FIGURE 11. THIOVEC® NOZZLE WARM GAS DEFLECTION HYSTERESIS LOOP

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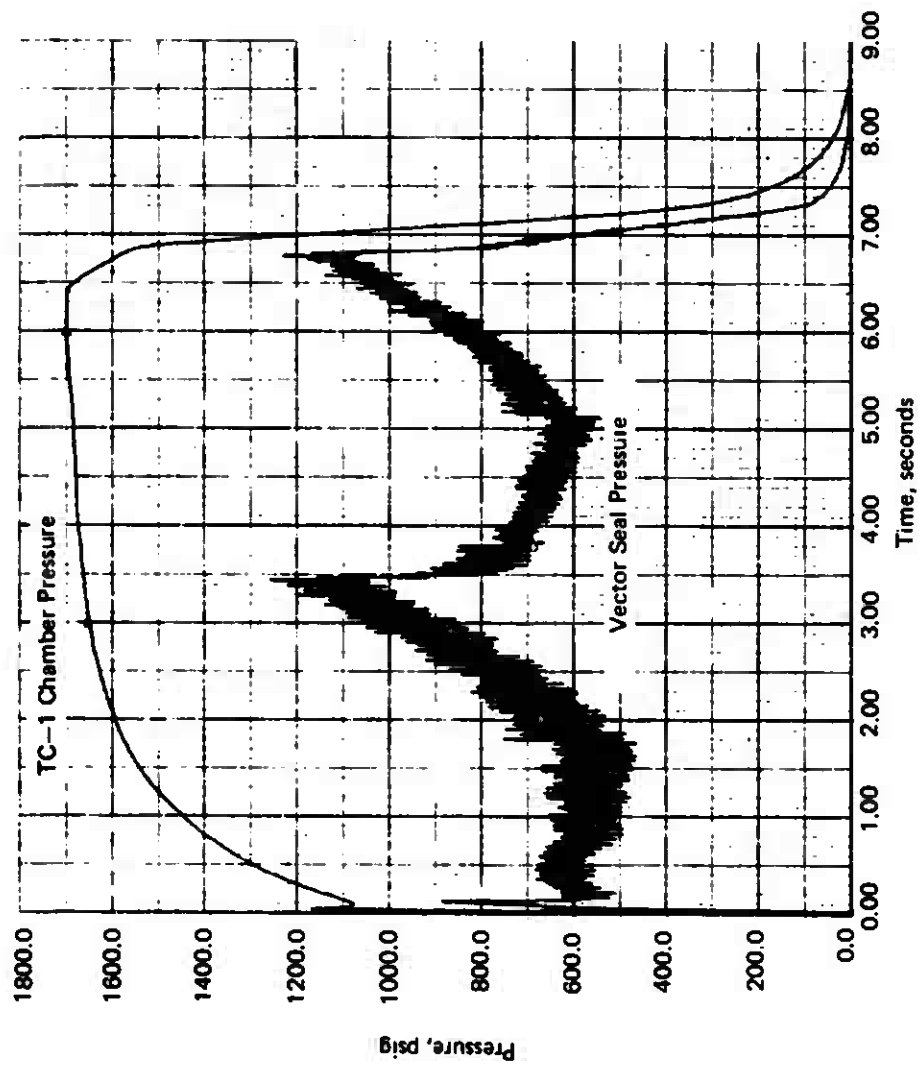


FIGURE 12. HYSTERESIS TEST, CHAMBER AND VECTOR SEAL PRESSURE

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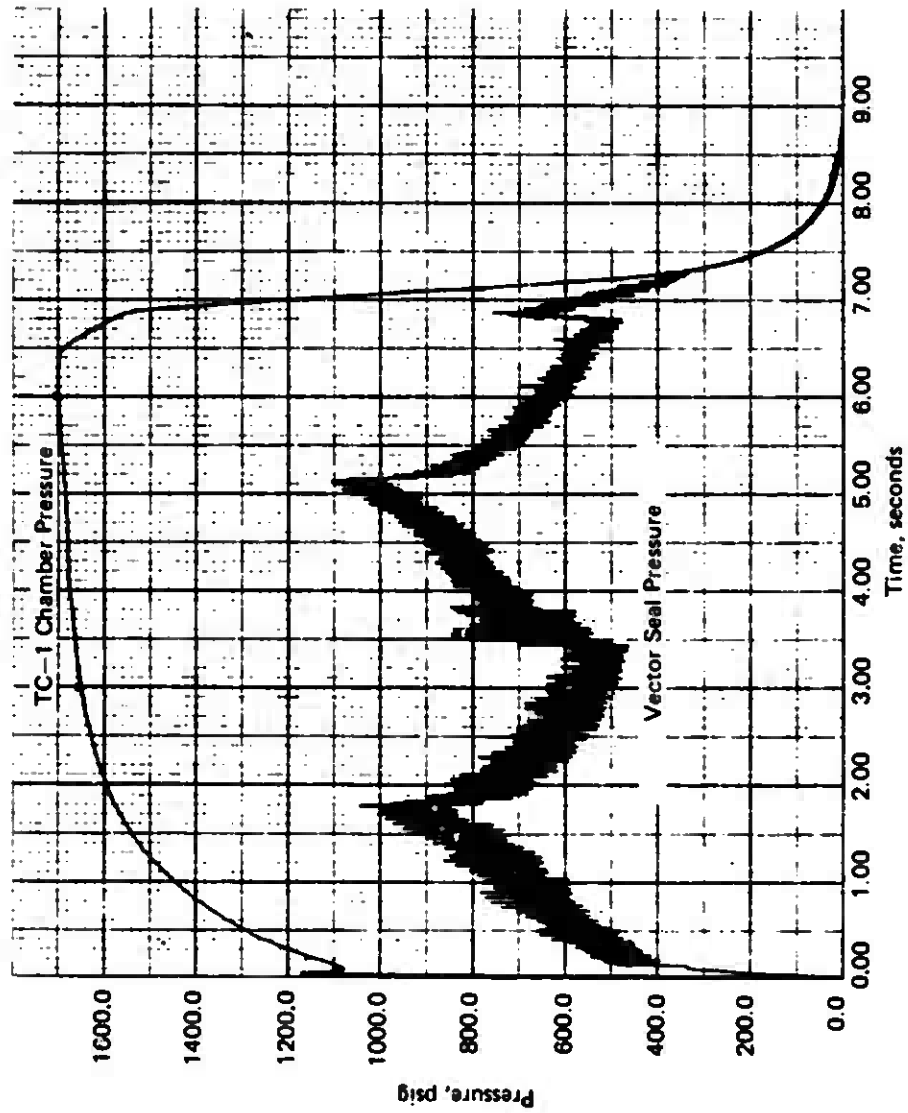


FIGURE 13. HYSTERESIS TEST, CHAMBER AND VECTOR SEAL PRESSURE

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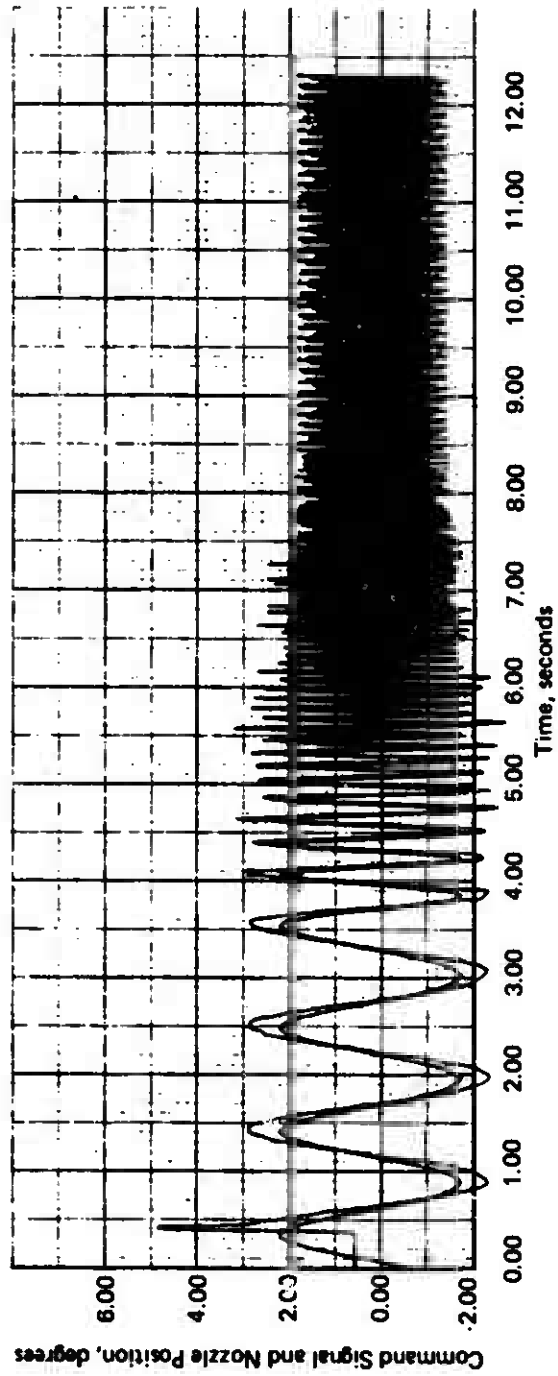


FIGURE 14. FREQUENCY RESPONSE, TEST RESULTS

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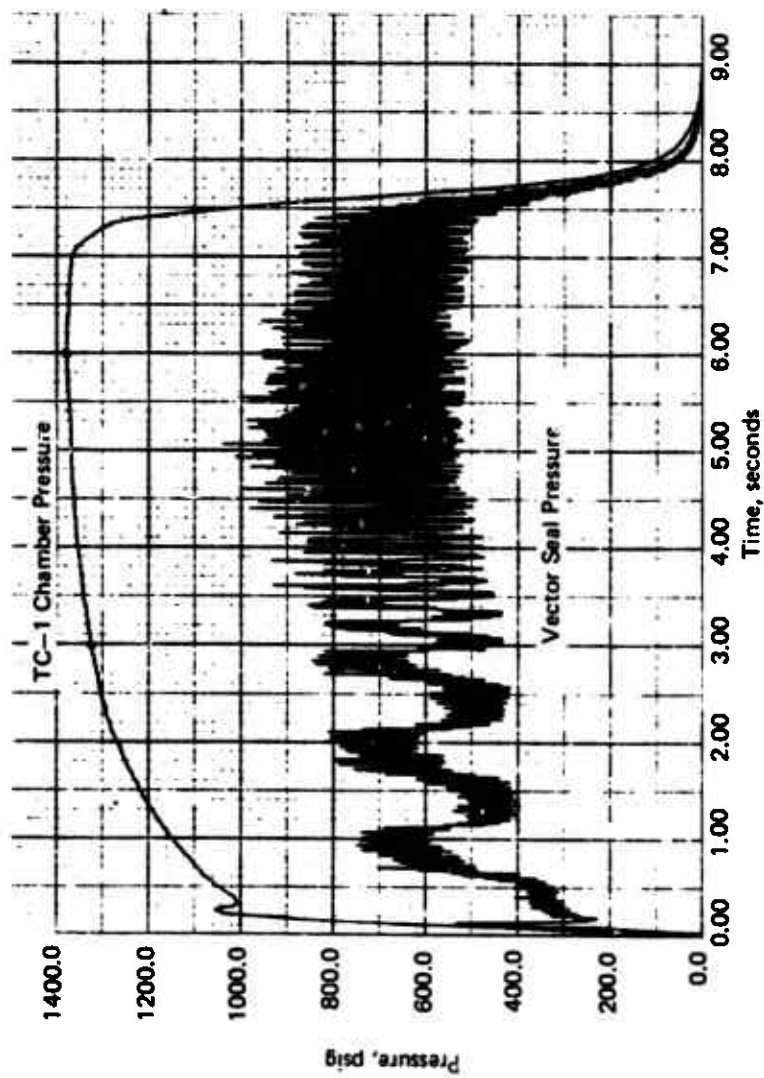


FIGURE 15. FREQUENCY RESPONSE TEST, CHAMBER AND VECTOR SEAL PRESSURE

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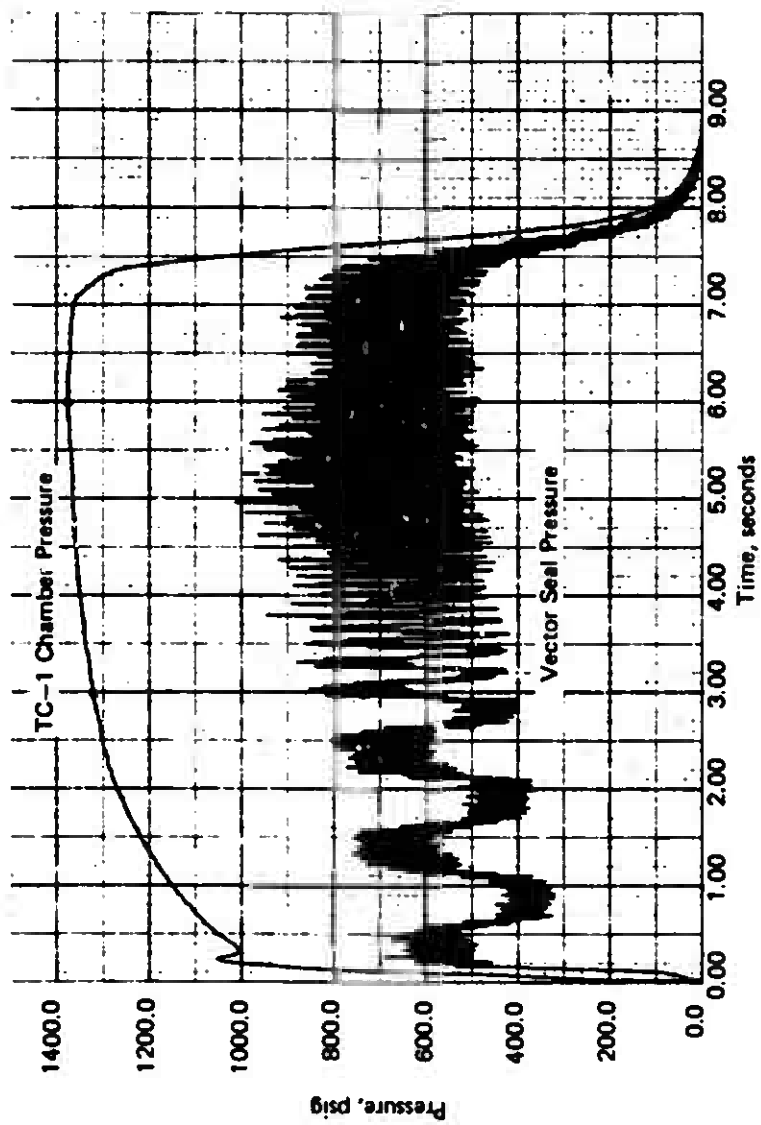


FIGURE 16. FREQUENCY RESPONSE TEST, CHAMBER AND VECTOR SEAL PRESSURE

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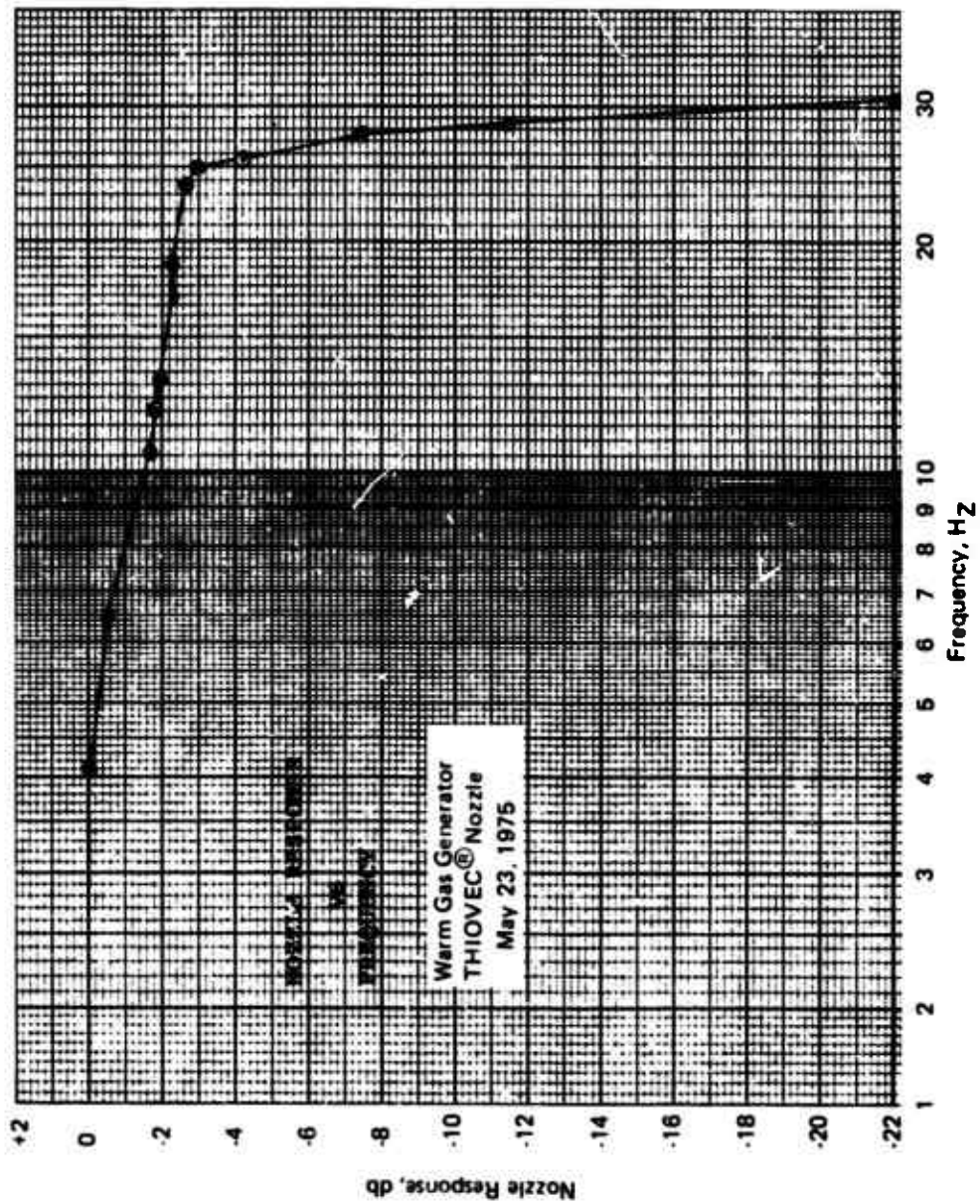


FIGURE 17. NOZZLE FREQUENCY RESPONSE

5.0 NOZZLE HARDWARE POST-TEST CONDITION

As noted previously, three consecutive tests were performed on the nozzle without dismantling and cleaning in between the tests. Figures 18 and 19 show the condition of the vector seal area and the deposits on the outer race and the seal. Figures 20 and 21 show the condition of the vector seal cover, including the inlet port through which the warm gas entered into the vector seal. Figure 22 shows the debris and the condition of the vector seal, O-ring, metal band, and Teflon back-up ring.

Figure 23 shows the condition of the outer race and the ball (inner race) after removal of the residual grease and debris. The axial burnish marks that can be seen on the outer race are normal and are not deleterious to the operation of the nozzle. It should be noted that there are no marks or scratches on the ball, indicating that there was ample clearance during the series of cold and warm testing.

Inspection of both the vector seal cover and outer race showed no sign of beating or other deleterious effects of any kind from the warm gas actuation tests. After disassembly, the nozzle was reassembled without rework other than cleaning and relubricating the components; in fact, the seal between the ball (inner race) and the outer race was not broken.

After reassembly, the breakaway torque and running torque was measured at 0° to 5° and 5° to 10° in both the extend and retract position. The values given in the following table were measured at an internal chamber pressure of 1500 psig to simulate motor chamber pressure.

TORQUE VERSUS NOZZLE POSITION

<u>Position, degrees</u>	<u>Breakaway Torque, in./lb</u>	<u>Running Torque, in./lb</u>
0 to 5 Extend	240	180
5 to 10 Extend	240	360*
0 to 5 Retract	240	130
5 to 10 Retract	240	360*

*This was the highest torque measured at the 10° position and within 5% of that predicted.

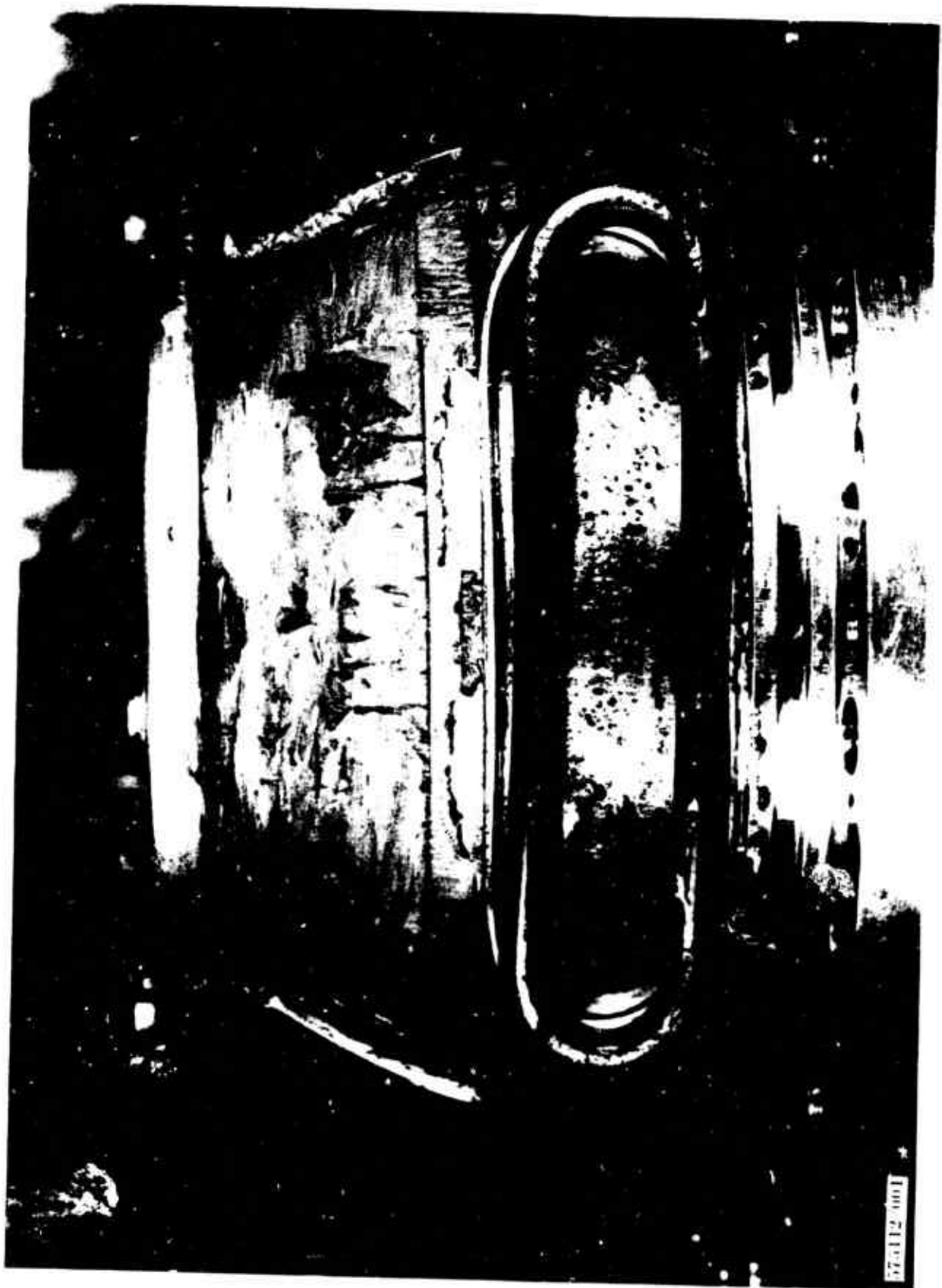


FIGURE 18. POST-TEST VECTOR SEAL ASSEMBLY NO. 1



FIGURE 19. POST-TEST VECTOR SEAL ASSEMBLY NO. 2



575112 /009

FIGURE 20. VECTOR SEAL COVER, POST-TEST, SEAL NO. 1



575112/010

FIGURE 21. VECTOR SEAL COVER, POST-TEST, SEAL NO. 2



FIGURE 22. VECTOR SEAL COMPONENTS, POST-TEST

575112 012



FIGURE 23. OUTER RACE, POST-TEST

6.0 CONCLUSIONS

- 1) The program objective was successfully accomplished in that all test results and the post-test condition of the hardware demonstrated the feasibility of actuating the THIOVEC[®] nozzle with warm gas.
- 2) Since the nozzle hardware was identical to that previously used with a hydraulic fluid actuation system, it can be concluded that the nozzle design features can remain identical and are independent of the type of actuation system, that is, either pneumatic or hydraulic.
- 3) Phase II of this program has successfully characterized the dynamic response of a warm gas actuated THIOVEC[®] TVC nozzle.
- 4) Although the nozzle control system was not adjusted or designed for optimum nozzle dynamic characteristics, the nozzle response, phase lag, and slew rate are well within expected requirements for underwater missile TVC systems.
- 5) The warm gas actuation system produced no nozzle overshoot.
- 6) Six repetitive warm gas tests using the same nozzle and actuation system hardware with only minimal clean-up after each test have demonstrated the absence of any adverse effects due to warm gas actuation of the THIOVEC[®] TVC nozzle.

APPENDIX ANOZZLE DESCRIPTION1.0 GENERAL

For descriptive purposes, the THIOVEC[®] TVC nozzle can be considered as consisting of four basic groups of components:

- 1) THIOVEC[®] Bearing Assembly
- 2) Actuator Mechanism
- 3) Actuation Control System
- 4) Nozzle Liner (insulation, throat, and exit cone)

An artist's presentation of a typical THIOVEC[®] nozzle with cutaway views THIOVEC TVC test are shown in Figures A1 and A2.

Only items 1) and 2) above are discussed in this appendix. The Actuation Control Section, item 3, is discussed in the text of this report. With respect to item 4), Nozzle Liner, the THIOVEC[®] nozzle structure, which interfaces with and supports the nozzle liner, is no different from that of other movable TVC nozzles.

2.0 THIOVEC[®] Bearing Assembly

The THIOVEC[®] nozzle is basically a ball-and-socket type TVC nozzle. The operating chamber pressure of a rocket motor produces a significant force on the movable ball portion of the nozzle. This force is termed "nozzle blow-out load." This load is reacted against the socket or stationary portion of the nozzle and, in most TVC nozzle designs, causes high friction at the ball-to-socket interface. The most significant feature of the THIOVEC[®] nozzle is the unique method of minimizing the frictional forces resisting movement of the ball within its socket. Frictional forces are low because of the lubricant between the inner race (ball) and outer race (socket) of the nozzle. The lubrication seals seal in the lubricant upon which the inner race "floats." Therefore, the inner race is in contact with only the lubrication seals and lubricant, producing a very-low-friction force resisting rotation of the inner race. Much of the friction force usually found in ball-and-socket type TVC nozzles is replaced by the lower viscous shear force at the ball-lubricant interface.

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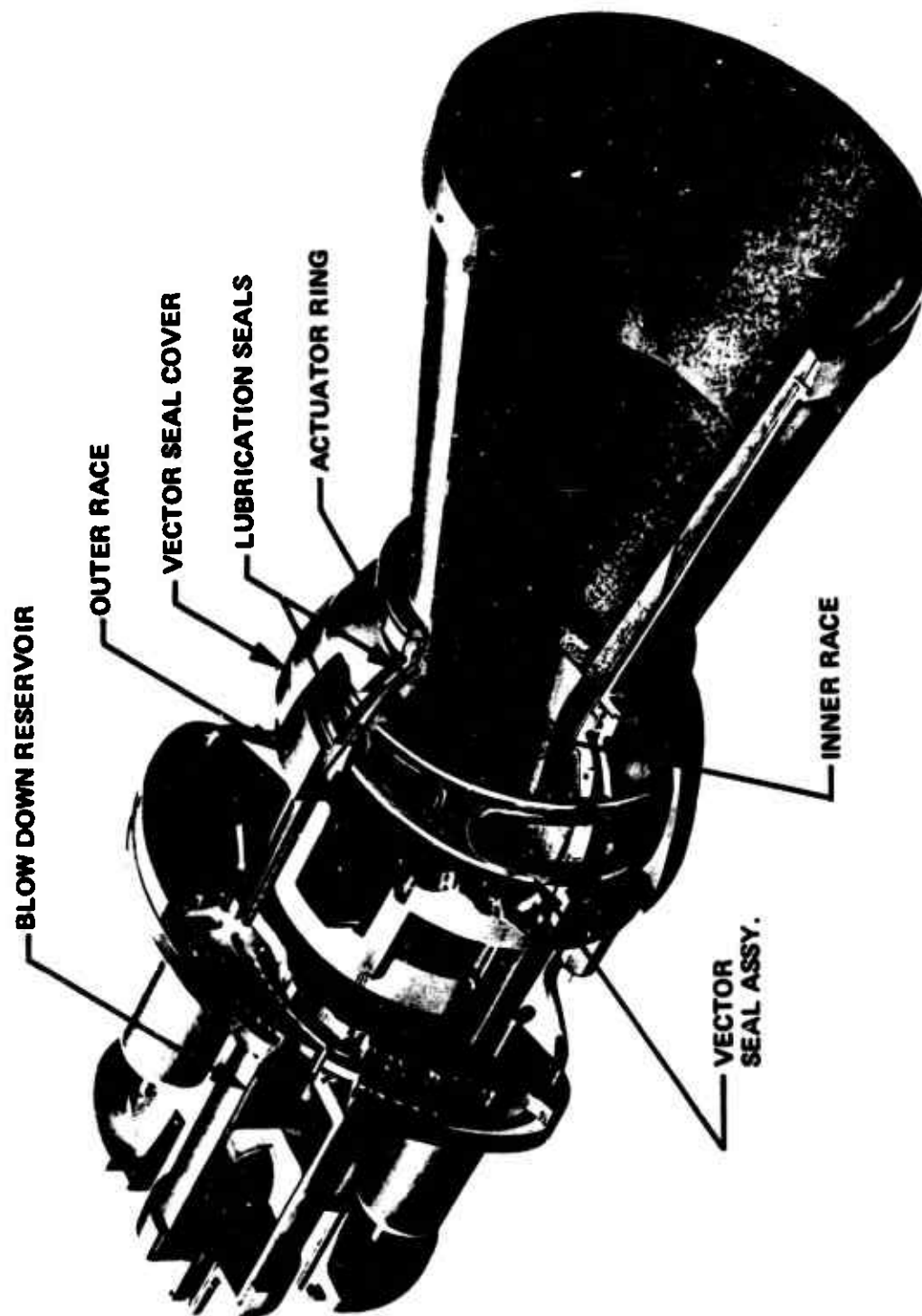


FIGURE A1. UNDERWATER THIOVEC® NOZZLE

UNDERWATER THIOVEC® TVC COMPONENTS

THIOVEC® TVC NOZZLE

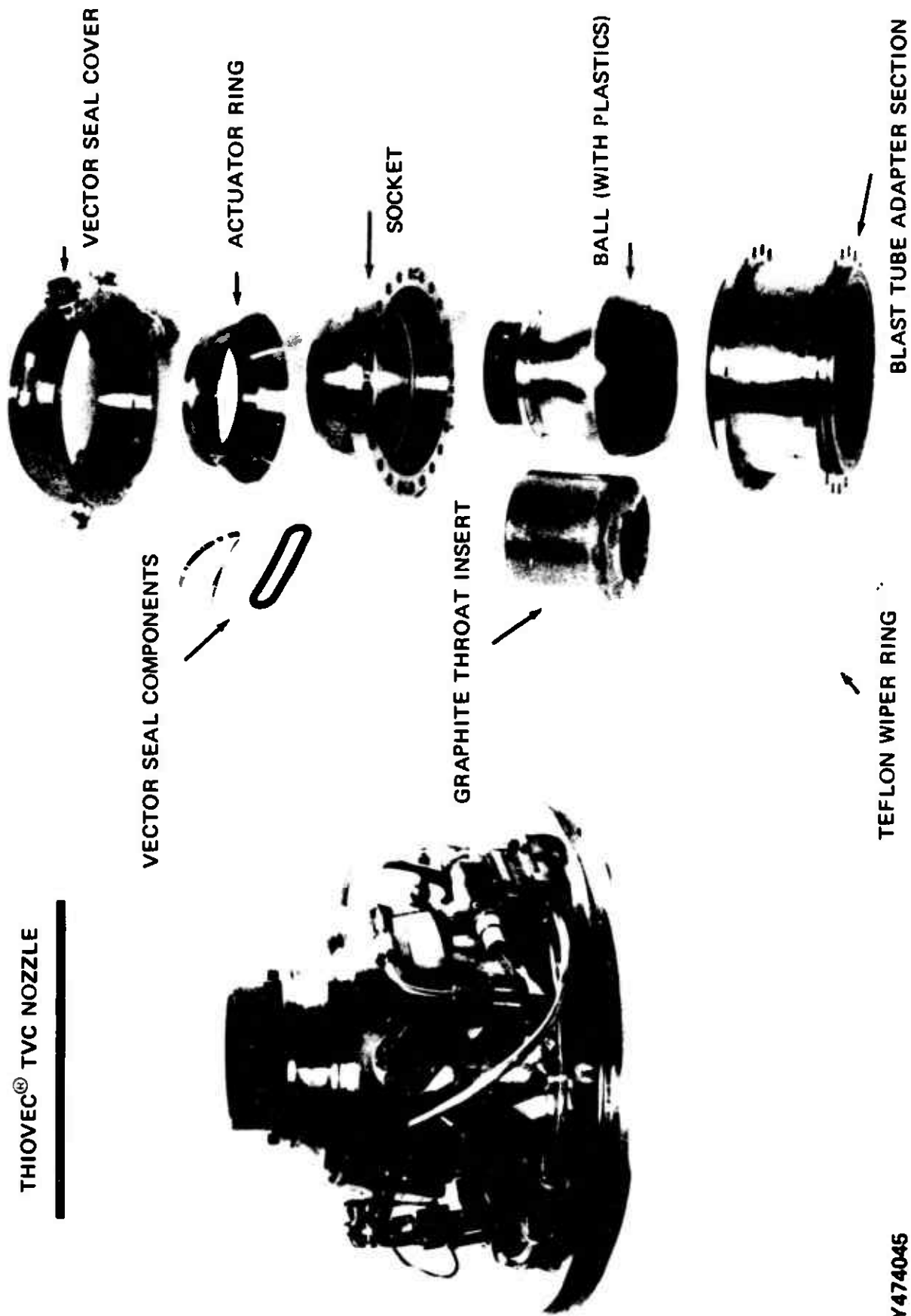


FIGURE A2. UNDERWATER THIOVEC® TVC COMPONENTS

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Axial displacement of the inner race occurs in the aft direction at a rate proportional to nozzle blowout load produced by chamber pressure and the axial load produced by the hydraulic actuation system. The nozzle blowout load pressurizes the lubricant, and the subsequent force balance achieved supports the "ball" in its "socket." Axial displacement of the inner race is limited by the extent to which the O-ring lubrication seals are displaced in their grooves and the outer race deflected by the lubrication pressure generated.

3.0 ACTUATION MECHANISM

Low resistive torques attainable with the use of the THIOVEC[®] bearing permit the use of a compact actuation system in place of conventional external actuators. The operating principle of the THIOVEC[®] nozzle actuation system is conceptually illustrated by the piston-actuated nozzle shown in Figure A3. When piston A is extended to maximum length, the nozzle is pitched downward, simultaneously retracting piston E. To deflect the nozzle upward, piston B is extended while piston A is retracted. To obtain deflection in the yaw axis, two additional pistons located 90 degrees circumferentially from piston A and B, respectively, would be required. Motion in planes intermediate to the pitch and yaw planes is accomplished by proportionate extension and retraction of adjacent pistons.

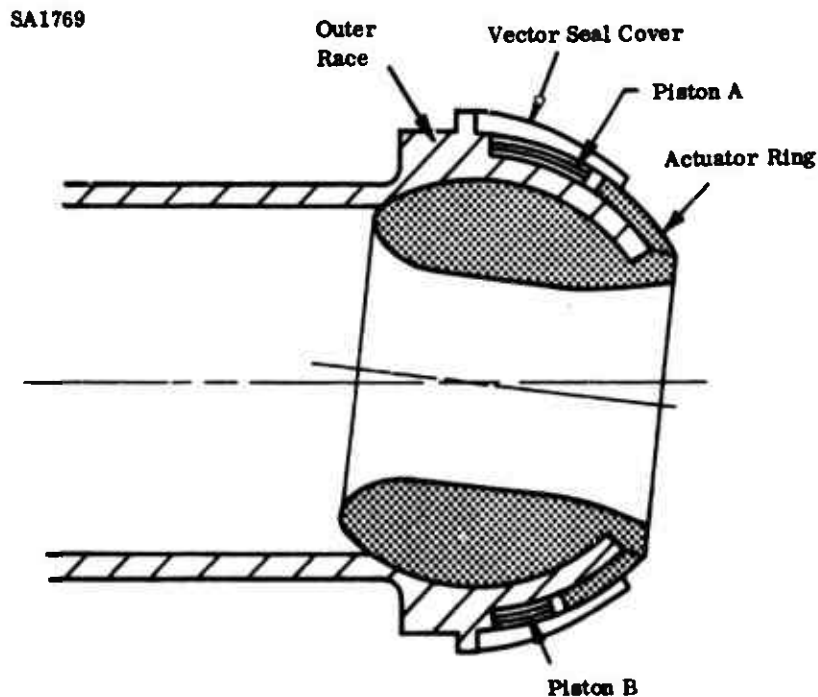


FIGURE A3. THIOVEC[®] ACTUATION SYSTEM CONCEPT

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In the THIOVEC[®] nozzle, piston functions are performed by four kidney-shaped flexible vector-seal assemblies located between the movable actuator ring and a face on the outer race. Kidney-shaped O-rings, with teflon back-up rings contained within their steel hands, are used as the vector seals.

The four vector seals are spaced 90 degrees apart. They flex, as illustrated in Figure A4, during nozzle movement. Figure A4 shows the approximate shape of the four seals at the null, maximum pitch up, and minimum pitch down positions when each seal is viewed perpendicular to the nozzle longitudinal axis. The vector seals are filled with hydraulic fluid that is contained by the inner surface of the vector seal cover and the outer surface of the outer race. Thus, when pressure is applied to the hydraulic fluid, the vector seal attempts to attain a circular form. The actuator ring is forced away causing the nozzle to deflect. The vector seal, 180 degrees from the pressurized seal, is vented to allow nozzle movement.

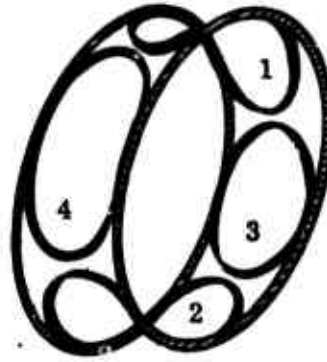
In Figure A4, note that when the nozzle is vectored in the pitch direction, the yaw seals assume irregular shapes. This produces unbalanced forces tending to rotate the vector seals about the longitudinal axis. In designs such as the Harpoon THIOVEC[®] nozzle, where the vector seals are not interconnected but separated, it is necessary to restrain each vector seal in its circumferential position by mechanically mating it with the actuator ring and outer race. Rotation of the inner race is resisted by keys mating with longitudinal slots in the actuator ring and attached to the outer race.

Because the vector seal actuation mechanism is contained between the fixed and movable nozzle parts, the nozzle is said to be internally actuated as compared to a TVC nozzle with conventional external actuators.

From the design standpoint, the retracted (compressed) versus the extended (expanded) position of the vector seals must be analyzed. When compressed, the vector seal is longer in the circumferential direction, resulting in an increased effective piston area. Thus, when hydraulic pressure is applied, a force is applied to the actuator ring, a result which, in large, restores torque about the nozzle pivot point. On the other hand, when the vector seal is fully extended, the seal is shorter in the circumferential direction, resulting in a decrease in the effective piston area and providing a reduced torque. Therefore, the piston area varies with the nozzle position. The torque developed is proportional to the piston area times the pressure in the seal.

The three basic torques resisting nozzle movement are lubrication-seal friction, vector-seal friction, and internal aerodynamic spring torque. Aerodynamic torque is minimized by designing the nozzle throat near the nozzle pivot point.

Actuation fluid is supplied to the vector seals through electromechanical servocontrol valves. These are connected by a manifold arrangement. Two servocontrol valves are required for omniaxial nozzle motion. As either valve permits pressurization of one vector seal, it simultaneously vents the opposite vector seal.



Pitch Vector Seals 1 and 2

Yaw Vector Seals 3 and 4

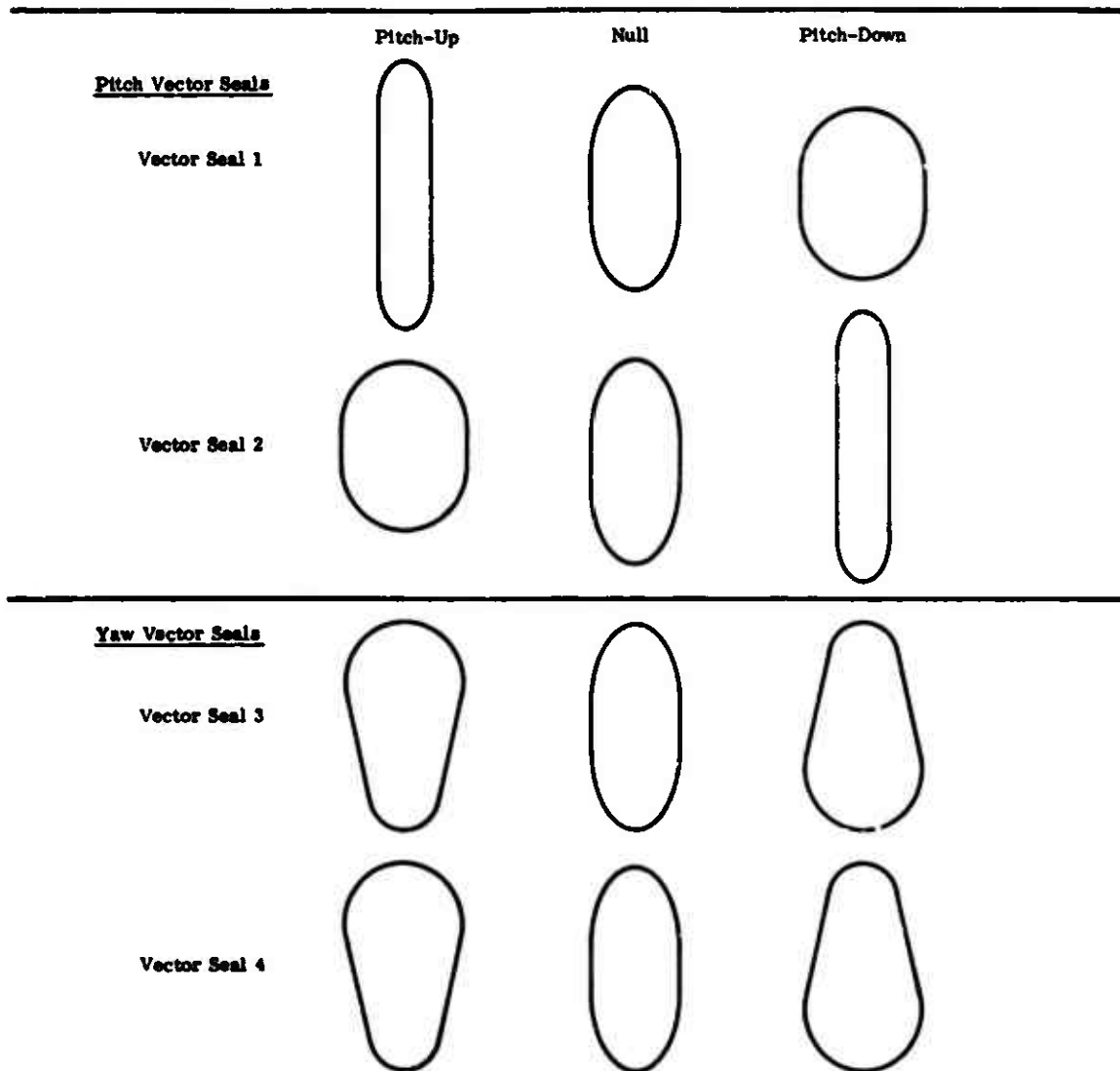


FIGURE A4. VECTOR SEAL SHAPES VERSUS NOZZLE PITCH POSITION